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COMPUTATIONAL STUDY OF SWEPT-FIN AERODYNAMIC HEATING FOR THE 105MM M774

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The 105mm M774 is a high velocity, long l/d, fin stabilized projectile. Recent test firings by LCWSL at Yuma Proving Ground, Arizona, revealed that the stabilizing fins were being severely reduced in span due to aerodynamic heating. This brief computational study examines the in-depth temperature response of a thin, swept fin to aerodynamic heating for a series of fin geometries in an effort to determine if a minor design modification can be found which will result in improved performance of the swept fin. The computational results

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20. ABSTRACT (Continued)

indicate that the aerodynamic heating can be significantly reduced by a relatively small increase in the sweep angle of the fin.

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I. INTRODUCTION

The 105mm M774 is a high velocity, long l/d, fin stabilized projectile. During recent test firings, the stabilizing fins were found to be significantly reduced in span due to aerodynamic heating. The reduction in span resulted in loss of flight stability for ranges greater than 2.5 km. These test firings were conducted for rounds which were temperature conditioned to 336. K.

This brief computational study was carried out in order to examine the in-depth temperature response of the fin to aerodynamic heating for launch conditions which resulted in significant erosion of the fins. A series of computations has been carried out for fin geometries in which the fin is modeled as a planar two-dimensional shape. The modeling includes the effect of the .0635mm thick aluminum oxide hard coat which is used to provide protection from aerodynamic heating. The effect of small changes in fin sweep angle and fin thickness are examined. An additional series of computations is reported in which the fin is modeled as a one-dimensional slab to examine the temperature response of the fin within the gun bore.

The results of the computations are presented as plots of the in-depth temperature at specific times in the flight trajectory and as temperature versus time for specific locations on and within the fin. By comparing the results for the current and modified fin geometries, the relative effect of the modifications on the range of the projectile is then determined. A recommendation is made for modification of the fin geometry. Recommendations are also made to achieve a capability for modeling the swept fin as a three-dimensional shape.

II. COMPUTATIONAL TECHNIQUES

A. In-Flight Modeling

1. Heat Transfer Coefficient.

The effect of the aerodynamic heating applied to the fin may be represented by a function of a heat transfer coefficient and recovery temperature which are functions of space and time. These parameters, which may be determined independent of the heat conduction within the fin by application of a cold-wall heat transfer boundary condition at the surface of the fin, are calculated using the ASCC-79 code as modified for planar shapes.[1] The velocity-time relationship of the M774 projectile used for input to the ASCC-79 code is shown in Figure 1.

Local heat transfer coefficients and recovery temperatures were determined for combinations of parameters listed in Table 1. The parameters of greatest interest are the fin sweep angle and the fin thickness.

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1. *Suchsland, K.E., "Aerothermal Assessment of Projectiles Using the ABRES Shape Change Code (ASCC)," Acurex Report TM-80-31-AS, June 1980.*

TABLE 1. SWEPT FIN GEOMETRIES CONSIDERED IN STUDY

Thickness mm	Sweep Angle Degrees	Coating Thickness mm
1.90	68.8	0.0635
2.03	71.0	0.127
2.16	75.0	0.0
	80.0	

2. Heat Conduction.

The in-depth, unsteady temperature response has been calculated using a code (GENDROP) which solves the two-dimensional, unsteady heat conduction equation with a fully implicit finite-difference computational technique. The code was developed by Dwyer.[2] The code is formulated in generalized coordinates which facilitates computations for arbitrary geometries.

A drawing depicting the M774 fin simplified geometry is shown in Figure 2. The fin geometry has been modeled as a thin flat plate with a leading edge radius equal to the half thickness of the plate. The computational grid is shown in Figure 3. The computations were carried out with a grid consisting of 10 points across the hardcoat layer and 30 points across the half thickness of the fin. Forty grid points were spaced in the longitudinal direction.

The boundary conditions are indicated below:

at time = 0; Temp = 336. K

at outer boundary

$$h\,(H_{aw} - H_{wall}) = -k(dT/d\eta)$$

at inner boundary

$dT/d\eta = 0$; symmetry condition

at material interface

$$-k(dT/d\eta)_a = -k(dT/d\eta)_b$$

at downstream side

$-k(dT/d\xi) = 0$; symmetry condition

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2. *Dwyer, H.A., Kee, R.J., and Sanders, B.R., "Adaptive Grid Method for Problems in Fluid Mechanics and Heat Transfer,"* AIAA Journal, *Vol. 18, No. 10, October 1980, pp. 1205-1212.*

The material interface was coupled by requiring equal heat flux from both materials at the junction. The parameters for the computations and the identification of the cases run are summarized in Table 2. The physical properties of the materials used for this study are listed in Table 3, except as noted in Table 2.

TABLE 2. TWO-DIMENSIONAL COMPUTATIONAL MODELING PARAMETERS

Case ID	Initial Temp, K	Fin Thickness, mm	Sweep Angle, degrees	Coating Thickness, mm	Fin Material
1	336.	2.03	68.8	.0635	Al
2	336.	2.03	71	.0635	Al
3	336.	2.03	75	.0635	Al
4	336.	2.03	80	.0635	Al
5	336.	1.90	68.8	.0635	Al
6	336.	2.16	68.8	.0635	Al
7	336.	2.03	71	.127	Al
8	336.	2.03	68.8	0.0	Steel
9	336.	2.03	68.8	0.0	Al
10	336.	2.03	71	.0635*	Al

*Density of coating = 4000. kg/m^3

TABLE 3. SWEPT FIN PHYSICAL PROPERTIES

Property/Material	Coating	Aluminum
Specific Heat J/kg - K	794.	869.
Thermal Conductivity W/m - K	30.6	43.4
Density kg/m^3	1850.	2800

B. In-Bore Modeling

The in-depth, unsteady heat conduction for the fin inside the gun tube has been modeled using a fully implicit one-dimensional finite-difference computational technique. The computations were carried out assuming a flame temperature of 3050 K and residence time within the gun tube of ten milliseconds. The boundary condition at the outer surface was determined using the relation:

$$h\ (3050 - T_w) = -k(dT/dx).$$

Results have been obtained for a wide range of the heat transfer coefficient, h, to examine the effect of the uncertainty in this parameter for the in-bore flow. The boundary condition at the midpoint of the fin was the adiabatic condition. The interface between the two materials was modeled by requiring the heat flux to be the same on both sides of the junction. The computational grid consisted of 10 points within the hardcoat layer and 30 points in the half thickness of the fin.

The identification of the computer runs and parameters of interest are summarized in Table 4.

TABLE 4. ONE-DIMENSIONAL COMPUTATIONAL MODELING PARAMETERS

Case ID	h	Mat'ls	Coating Thickness	Time Step	Initial Temp, K
A	5.72	2	.0635	.0001	336
B	.572	2	.0635	.0001	336
C	.0572	2	.0635	.0001	336
D	5.72	1	.0	.0001	336
S	57.2	2	.0635	.0001	336
T	5.72	2	.127	.0001	336

h, $kW/m^2 - K$
Coating Thickness, mm
Time Step, seconds

III. COMPUTATIONAL RESULTS

A. In-Flight Modeling

1. Heat Transfer Boundary Condition.

The results for the surface boundary condition obtained using the code ASCC-79 are illustrated in Figures 4 through 6. The result shown in Figure 4 compares the cold wall heat transfer coefficient along the fin surface at several times in the trajectory for the basic M774 fin geometry. The distance along the fin surface, s, has been nondimensionalized by fifty times the leading edge radius, L. This figure indicates that there is a significant change in the heat flux both as a function of time and position on the fin surface and serves to emphasize the importance of modeling the two-dimensional geometry of the fin and the velocity-time decay for the projectile.

The effect of the sweep angle on the heat transfer coefficient is shown in Figure 5. It is seen that the stagnation point heat flux is strongly affected by the sweep angle. A similar comparison for the effect of fin thickness is shown in Figure 6 which shows that small changes in fin thickness have little effect on the local heat flux.

These heat transfer rates are for a completely laminar boundary layer. Estimates for the location of boundary layer transition confirmed this to be valid.

The effect of the cold wall boundary condition was tested by comparing predicted values of local heat transfer coefficient for several values of wall temperature. The results indicated that the heat transfer coefficient and the recovery temperature are not strongly affected by the wall temperature and confirm the validity of the boundary condition used for the computations of heat conduction.

2. Unsteady Heat Conduction.

Results for the in-depth unsteady heat conduction for the fin during flight are shown in Figures 7 through 14. Comparisons are shown for the variation of temperature versus time at a single location and for profiles of temperature versus position at specific times in the flight.

The variation of the leading edge coating-metal interface temperature versus flight time for several sweep angles is shown in Figure 7. The sweep angle is seen to have a significant effect on the temperature at this position.

The computed results can be evaluated in light of the firing tests by choosing the leading edge temperature reached by the result for case 1 at a distance of 2.5 km (time = 1.7 sec.) as a reference point. This is a conservative choice since the M774 was flying well at that distance. The results suggest that, for a sweep angle of 75° or greater, the fin will have sufficient span to support stable flight for a range greater than 3 km.

The variation of the surface temperature at position P2, located nine leading edge radii from the leading edge (see Figure 3), as a function of the fin sweep angle is shown in Figure 8. This result is similar to that shown in Figure 7. The effect of fin thickness is illustrated in Figure 9. Small changes in the fin thickness are seen to have relatively little effect on the temperature response of the fin. Likewise, the coating thickness is shown in Figure 10 to have little effect on the temperature response at the leading edge coating-metal interface. A comparison of coated and uncoated fins is shown in Figure 11. This result predicts little effect of the coating on the temperature response of the fin which seems to be contrary to previous experience.

Figure 12 illustrates the effect of variation in the density of the coating on the stagnation point temperature. This result suggests that the density (porosity) of the coating can have a significant effect.

An example of the temperature profile across the fin at a specific time in the trajectory is shown in Figure 13. The temperature difference from the outer surface to the midpoint of the fin is seen to be about 5. K at .5 second decreasing to less than 2. K at 2 seconds which emphasizes the high heat conductivity of aluminum. This is further illustrated in Figure 14 where temperature contour plots are shown for specific times in the trajectory for case 1.

An alternative to using aluminum for the fin material is steel. Figure 15 shows a comparison of the leading edge temperature as a function of time in the trajectory between steel (case 8) and aluminum (case 1) fins. The result indicates very little change in the temperature of the fin at this position; however, since steel has a much higher melting temperature than aluminum, the steel fin has a considerable margin of safety. The effect of the different physical properties of the two metals is evidenced at positions away from the leading edge (not shown) where differences in temperature across the fin thickness of 10. K were observed.

B. In-Bore Modeling

Examples of the results of the one-dimensional modeling of the heat transfer from the propellant gases inside the gun tube to the fin are shown in Figures 16, 17, and 18. A comparison is shown in Figure 16 of the temperature profiles across the fin after ten milliseconds of heating for several heat transfer coefficients. The temperatures within the fin are seen to be sensitive to this parameter, with the temperature rise across the aluminum varying from less than one degree Kevlin for case C to 40 K for case A. The value of heat transfer coefficient used for case A is representative of that used for prediction of boiler tube heat transfer and may be thought of as an order of magnitude estimate of h for a gun tube. Further refinement of this estimate is needed, and work is currently progressing in this direction.

A comparison is shown in Figure 17 between results for two coating thicknesses and a result for an uncoated fin. The thicker coating is seen to have very little effect on the temperature rise within the metal fin. The final example, Figure 18, shows the temperature rise at the surface of the fin as a function of time for case A.

IV. DISCUSSION AND CONCLUSIONS

The computed results have been evaluated in light of the firing tests by choosing the leading edge temperature reached by the result for in-flight case 1 at a distance of 2.5 km (time = 1.7 sec.) as a reference point. An estimate has been made of the thermal response of the fin for a modified fin geometry by determining the time for the modified fin to reach this same temperature. This is a conservative choice since the M774 was flying at small angle of yaw at that distance. This time has further been related to a change in range using the trajectory plotted in Figure 1. The result of this analysis is summarized in Table 5 below.

TABLE 5. RELATIVE EFFECT OF FIN GEOMETRY MODIFICATIONS

Parameter Changed	Change	Effect on Range, dR
Sweep angle	68.8 - 71°	.44 km
Sweep angle	68.8 - 75°	> .5 km
Sweep angle	68.8 - 80°	>> .5 km
Fin thickness	2.03 - 2.16 mm	.28 km
Fin thickness	2.03 - 1.9 mm	- .28 km
Coating thickness	.0635 - .127 mm	.08 km
Coating thickness	.0635 - 0.0 mm	0 km

These estimates clearly show that changing the sweep angle of the fin strongly influences the aerodynamic heating to the fin.

The conclusions reached after considering the results of this computational study are summarized below.

1. The effect of the aerodynamic heating can be significantly reduced by increasing the sweep angle of the fin by a few degrees.

2. The density (porosity) of the coating is a significant factor in the thermal response of the fin.

3. A small change in the thickness of the coating does not have a significant effect on the thermal response of the fin.

4. A small change in the thickness of the fin has a small effect on the fin thermal response.

5. A fin made of steel allows for a considerable margin of safety with respect to effects of aerodynamic heating.

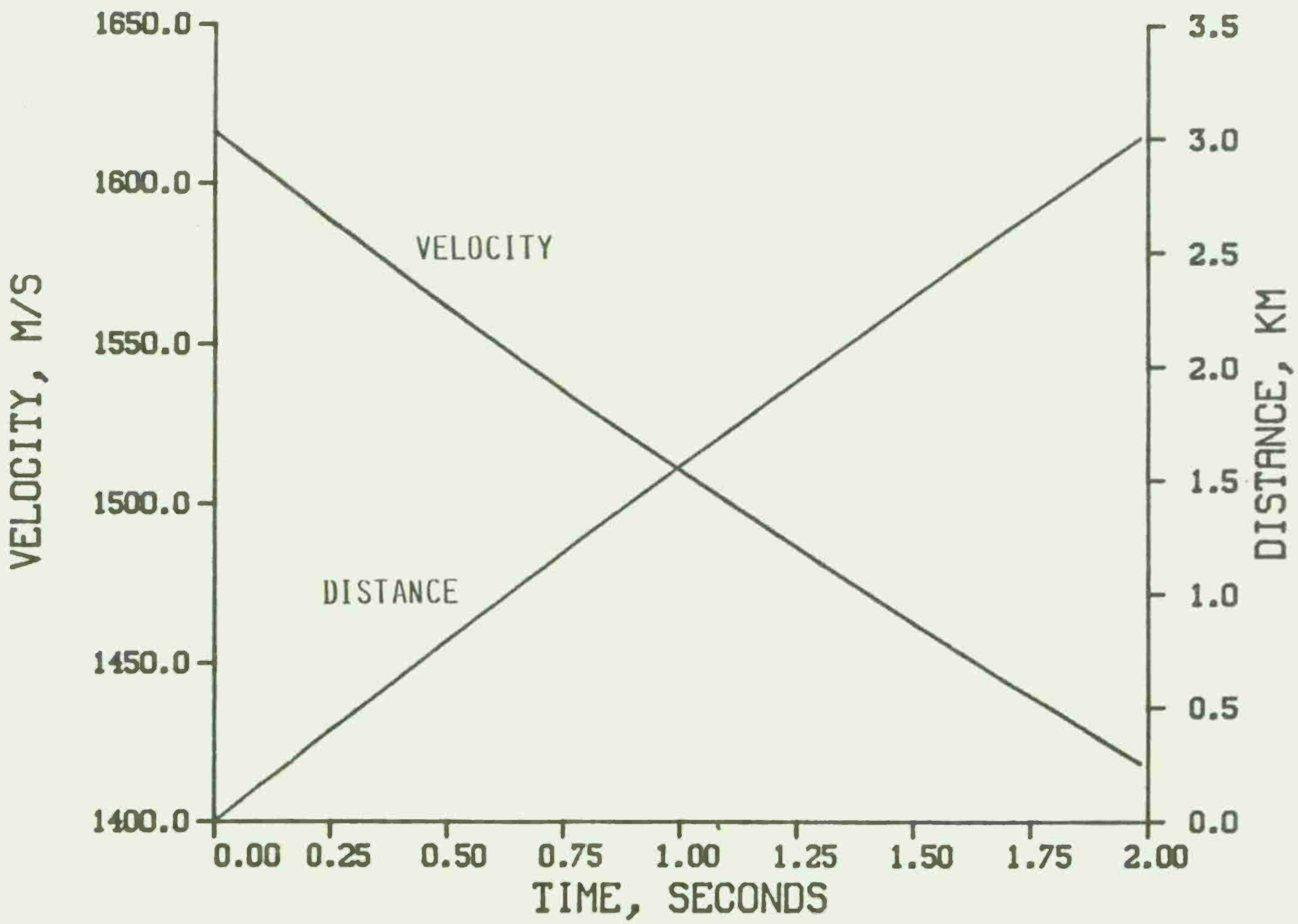
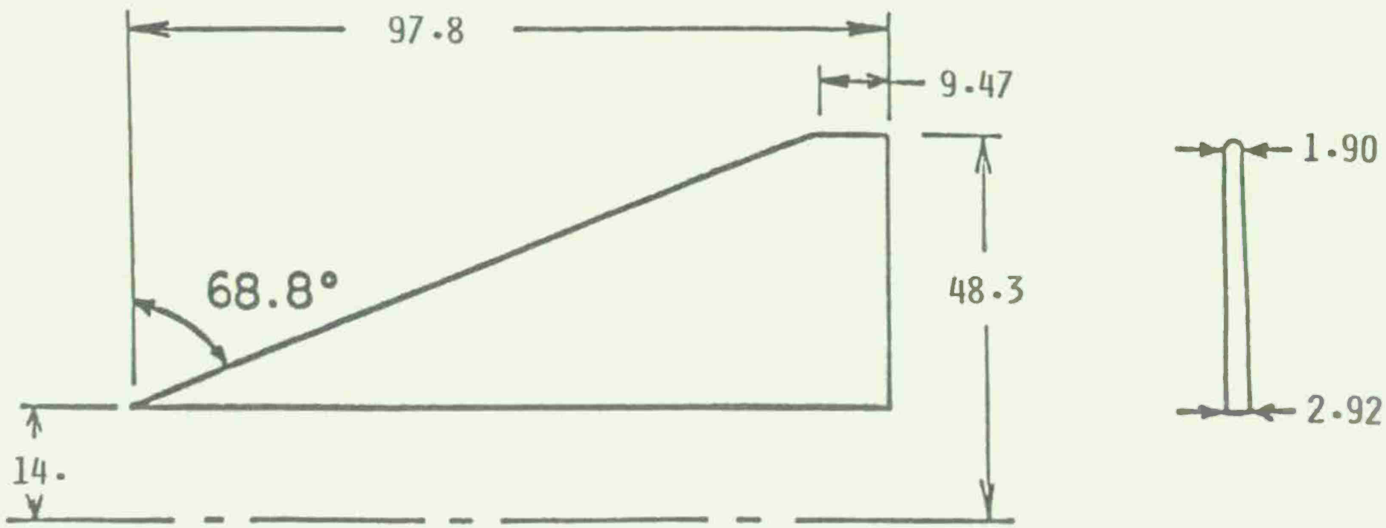


Figure 1. Velocity-Time Relation Used as Input for ASCC-79



DIMENSIONS IN MM

Figure 2. Simplified Drawing of the M774 Swept Fin

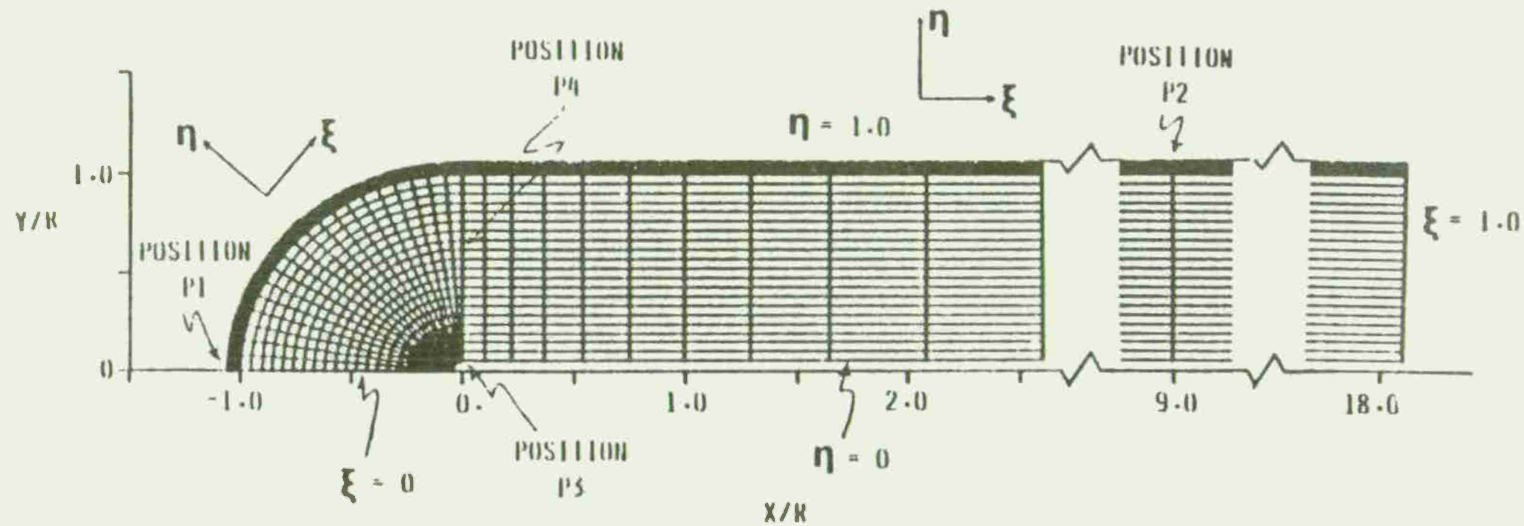


Figure 3. Computational Grid for 2D Computations

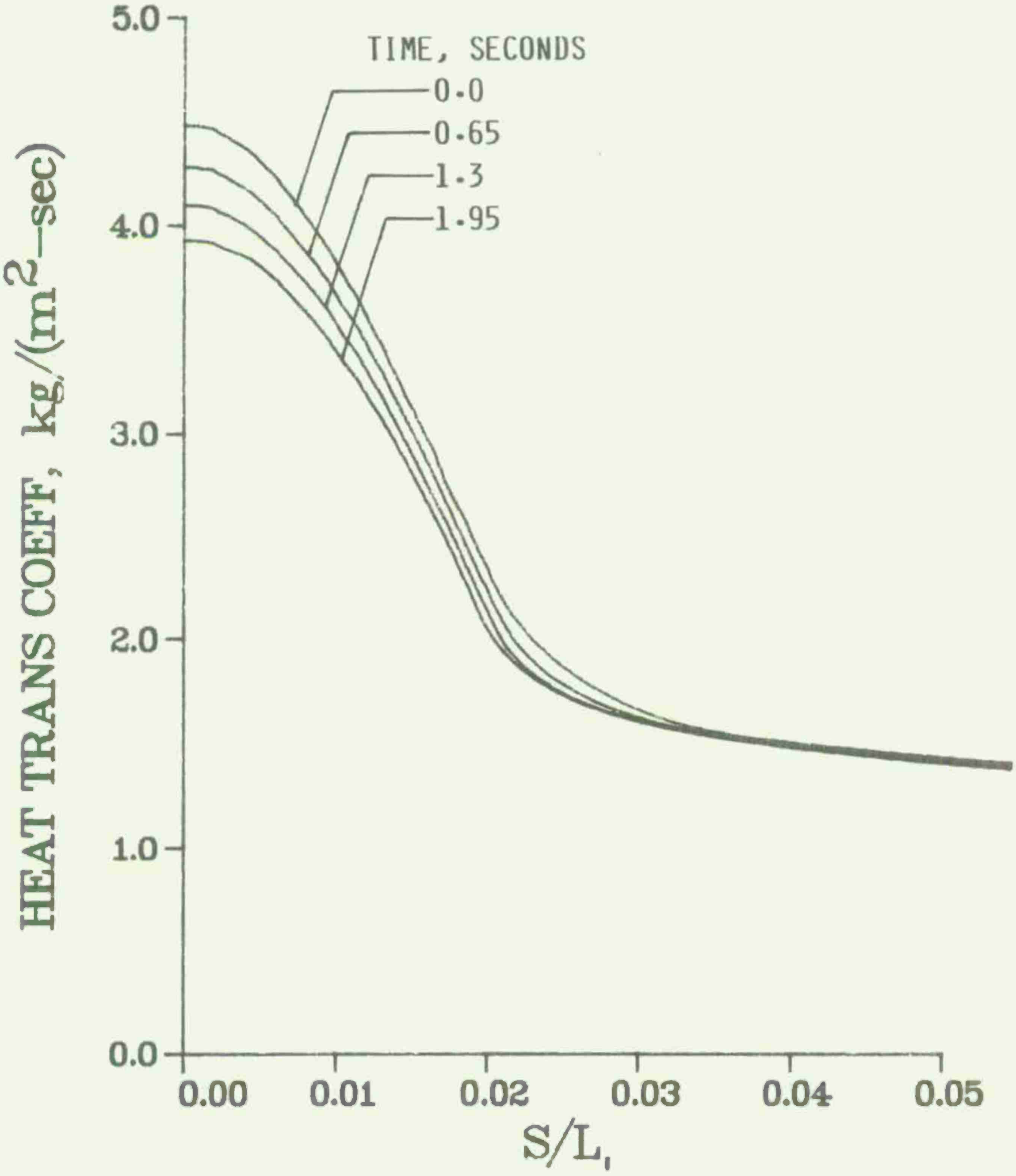


Figure 4. Cold Wall Heat Transfer Coefficient vs. Arc Length of the Basic Fin Geometry for Several In-Flight Times, Sweep Angle = 68.8°

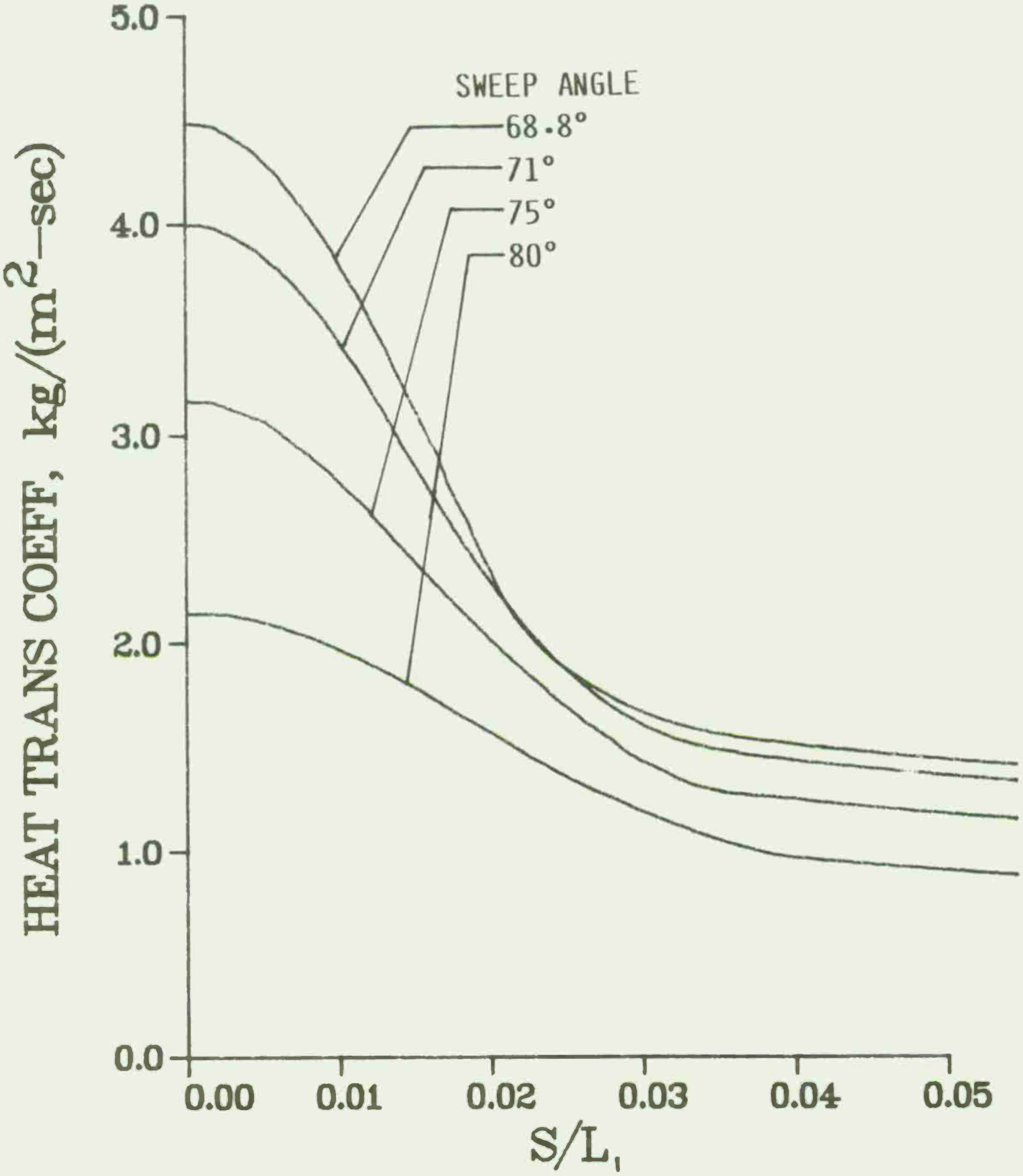


Figure 5. Cold Wall Heat Transfer Coefficients vs. Arc Length of the Basic Fin Geometry for Several Sweep Angles, t = 0 second

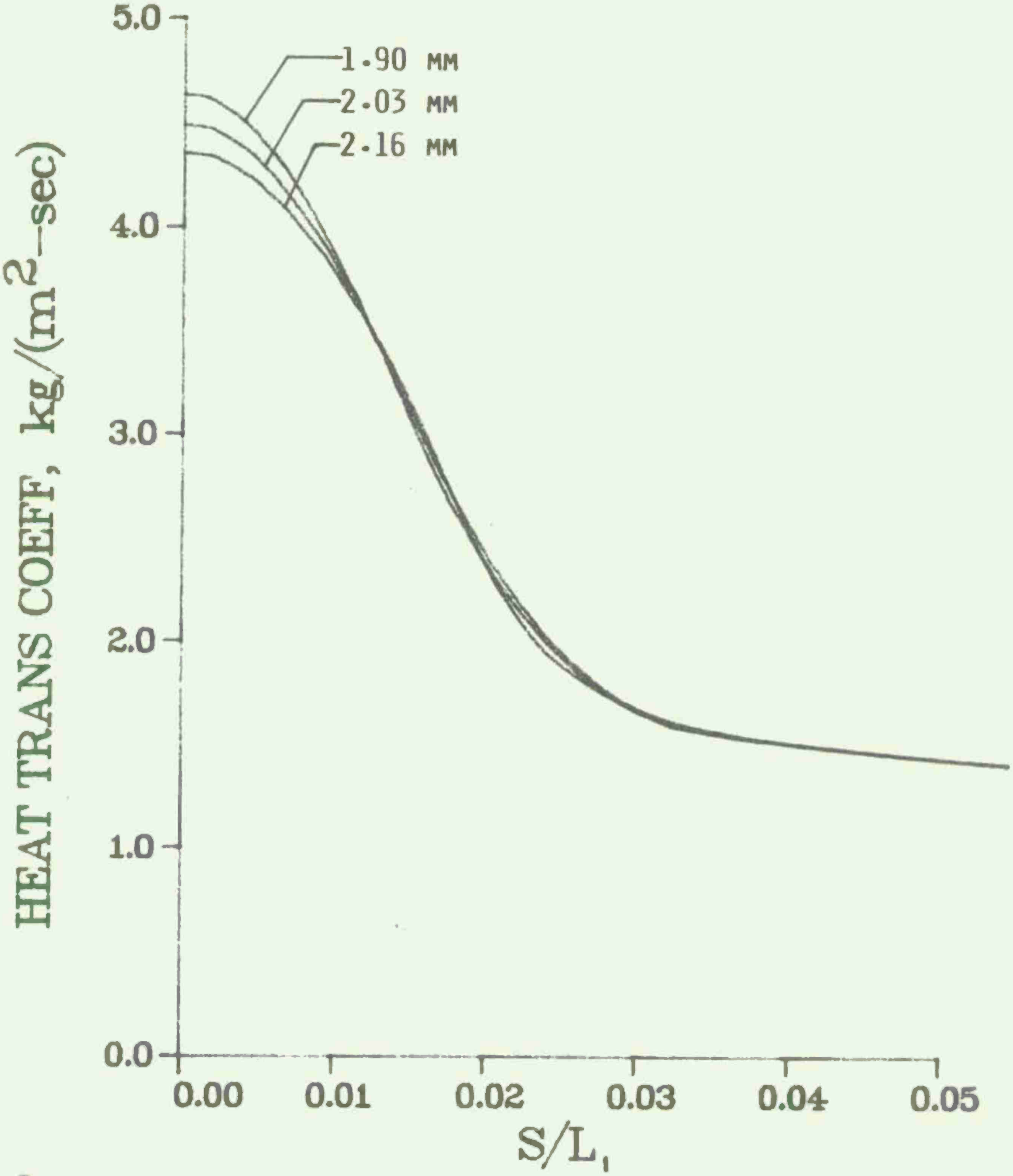


Figure 6. Cold Wall Heat Transfer Coefficient vs. Arc Length for Several Fin Thicknesses at a Sweep Angle of 68.8°, t = 0 second

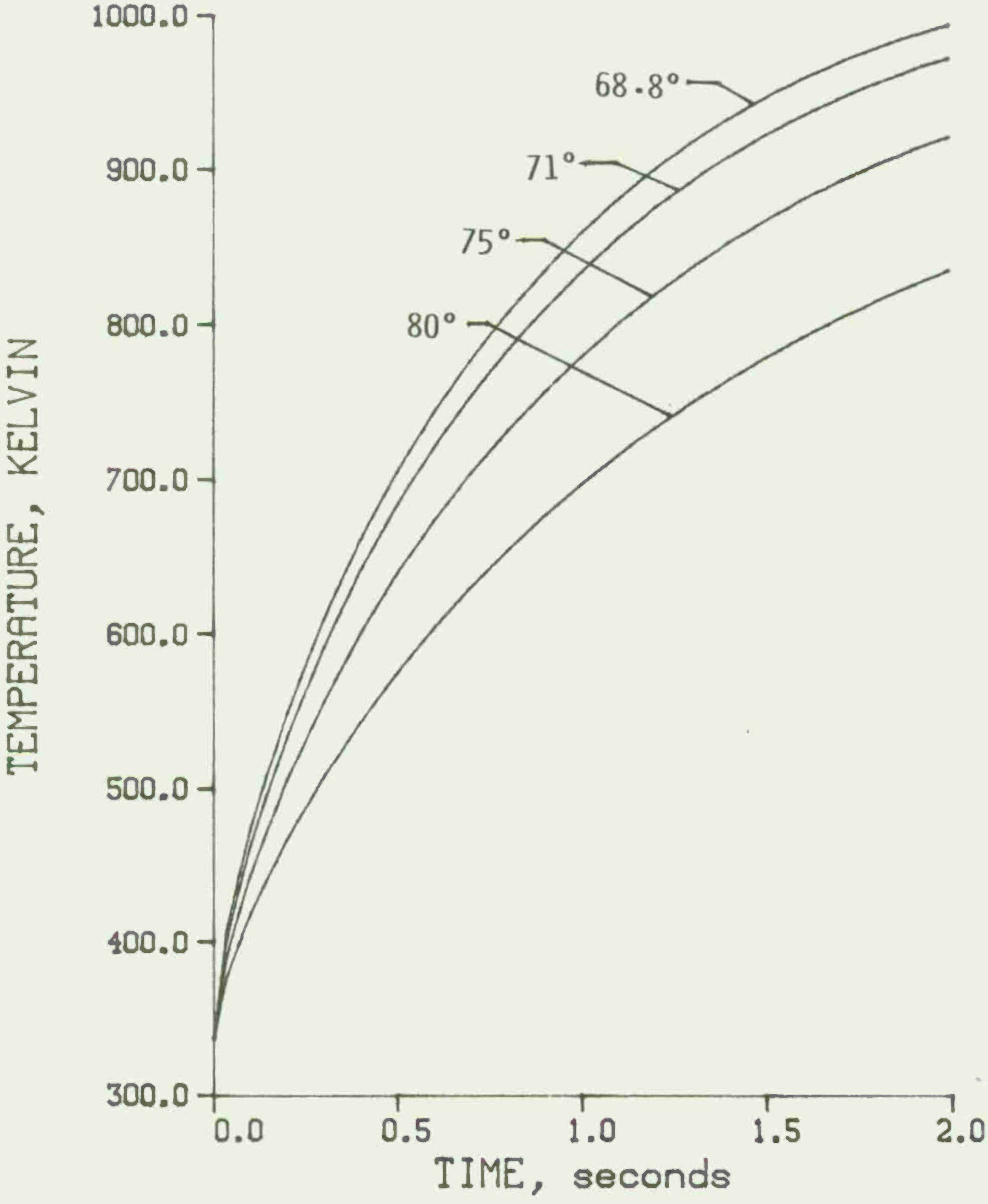


Figure 7. Temperature at the Leading Edge Coating-Metal Interface vs. Time as Function of Sweep Angle, In-Flight Cases 1, 2, 3, 4

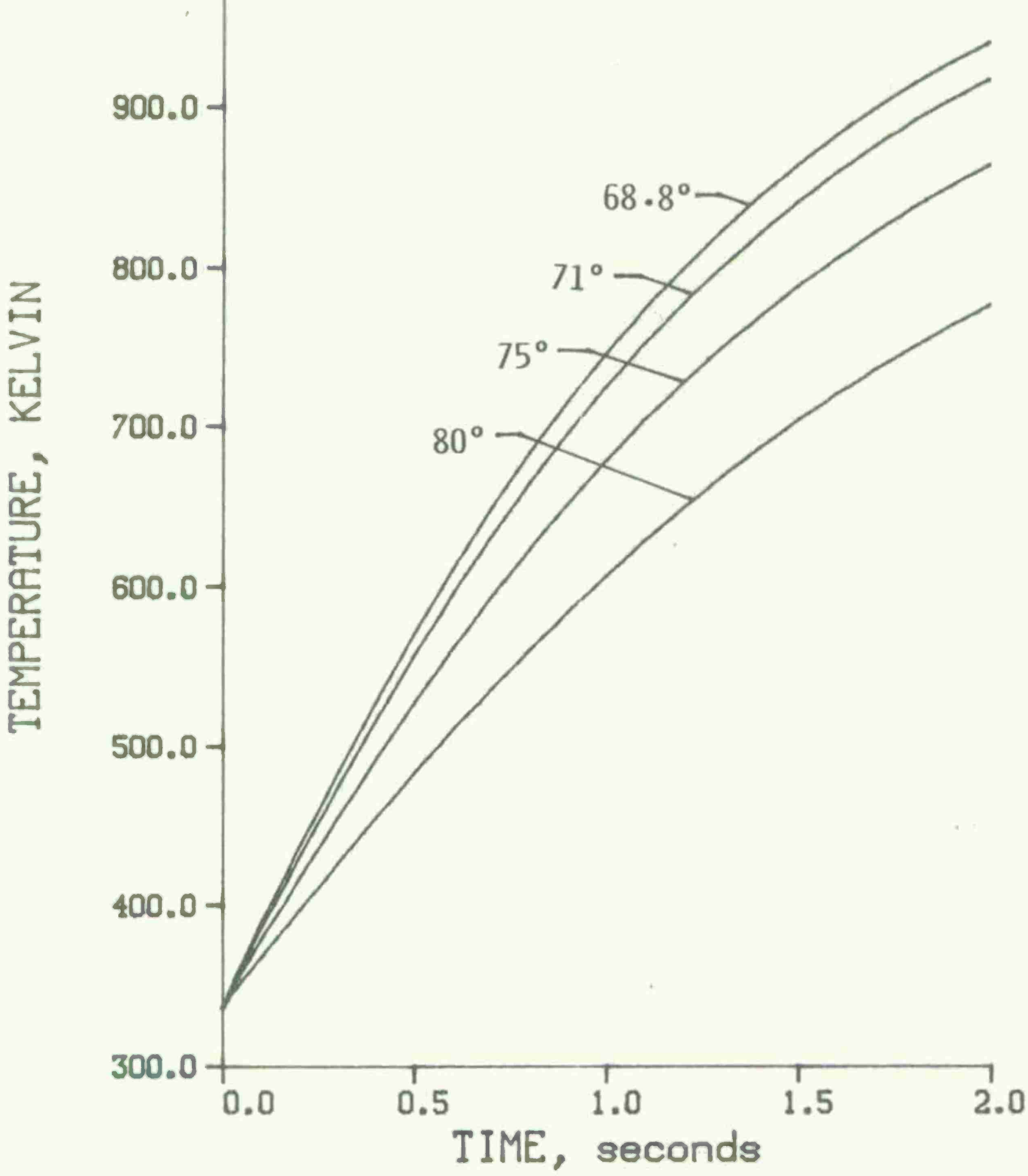


Figure 8. Surface Temperature vs. Time at Point P2 as Function of Sweep Angle, In-Flight Cases 1, 2, 3, 4

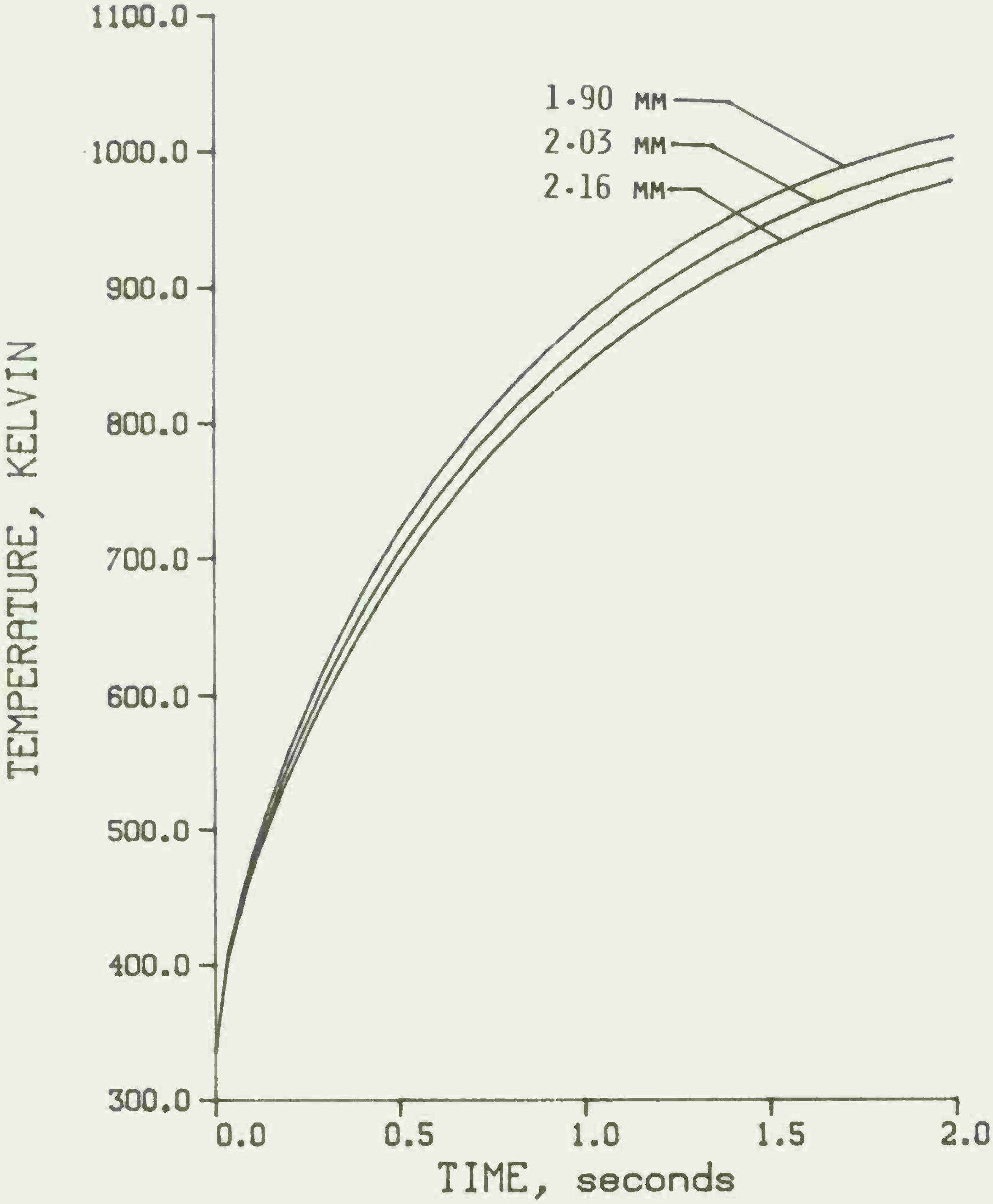


Figure 9. Temperature at the Leading Edge Coating-Metal Interface vs. Time as Function of Fin Thickness, In-Flight Cases 1, 5, 6

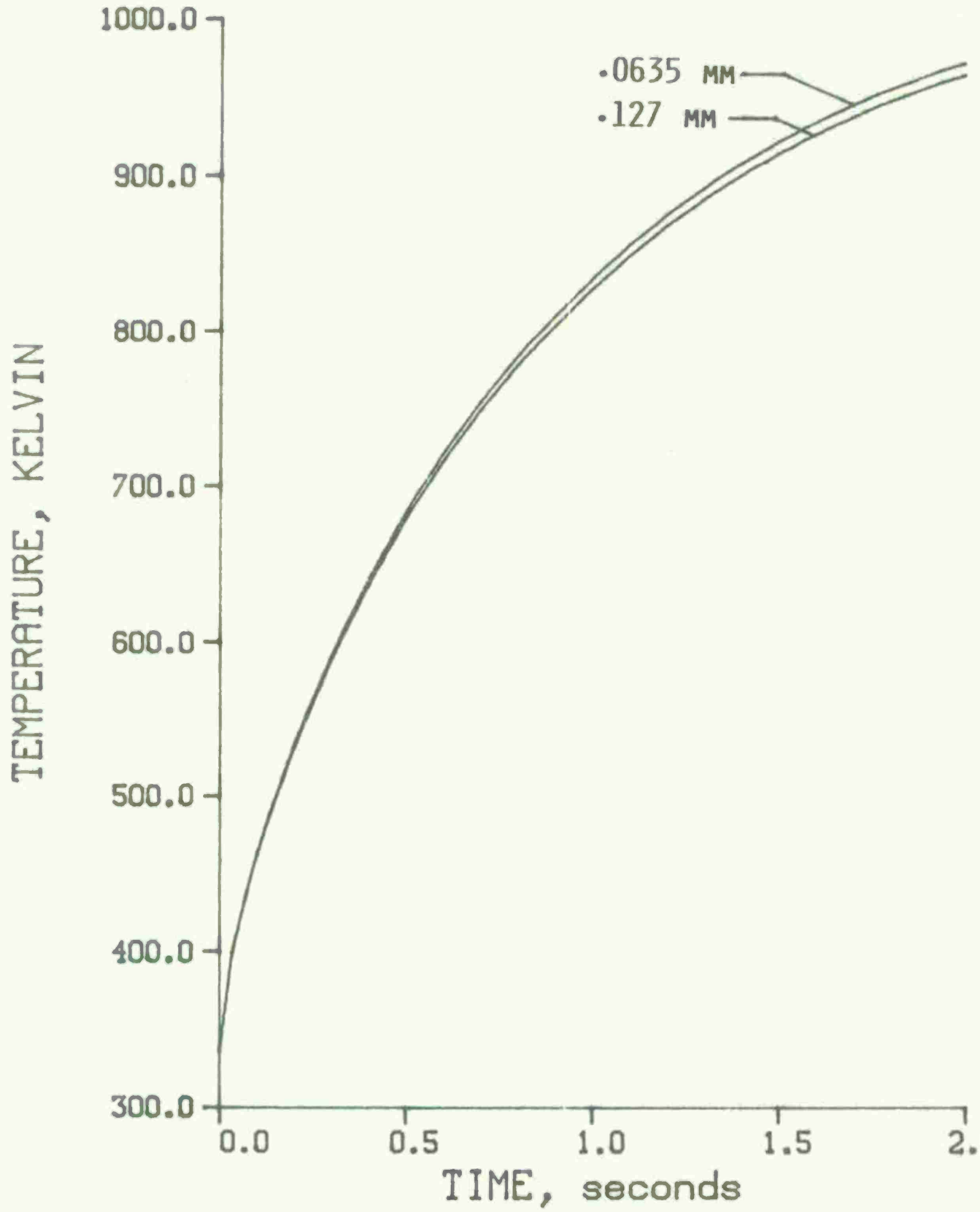


Figure 10. Temperature at the Leading Edge Coating-Metal Interface vs. Time as Function of Coating Thickness, In-Flight Cases 2, 7

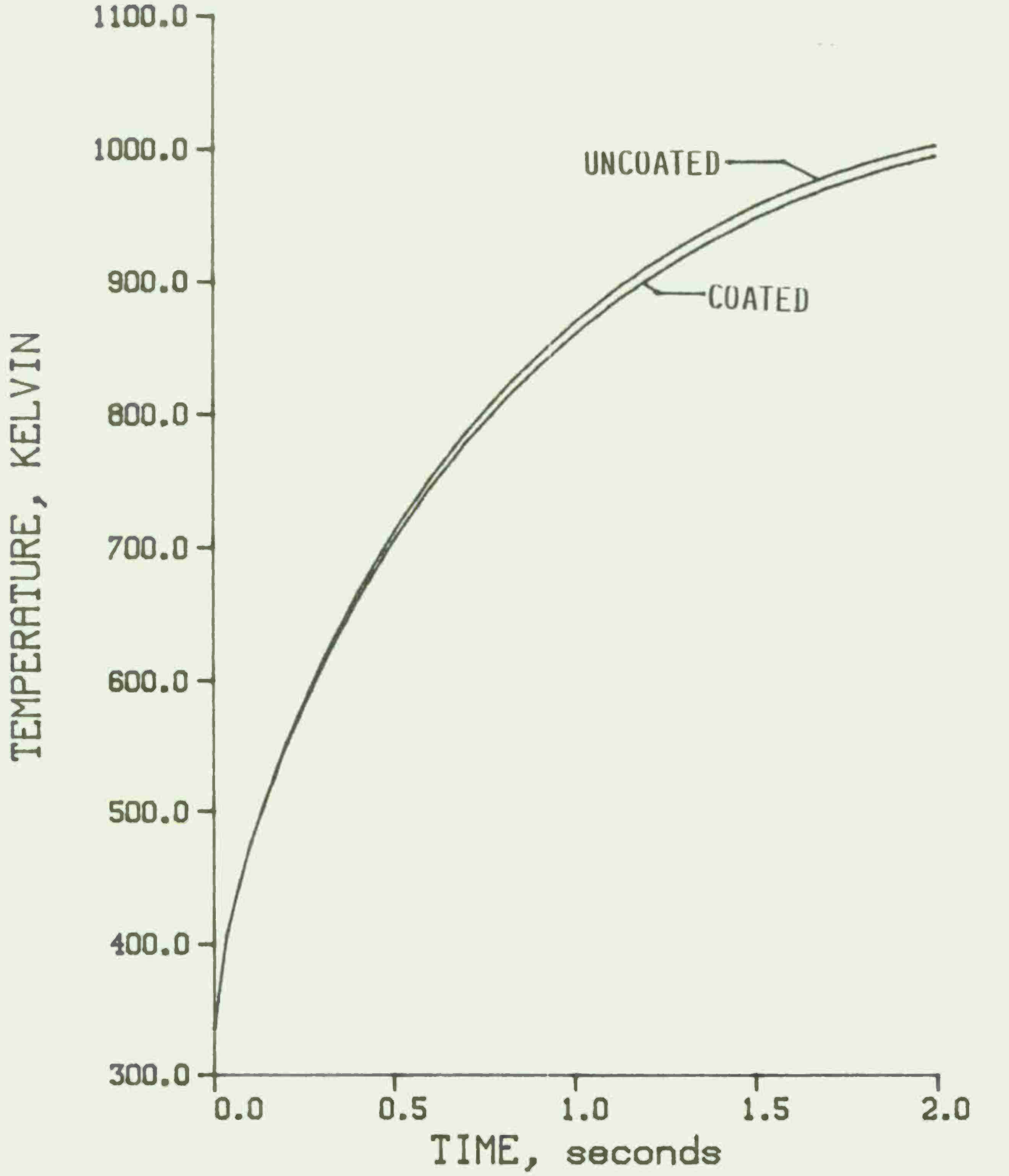


Figure 11. Temperature on Leading Edge Aluminum Surface vs. Time for Coated and Uncoated Fin, In-Flight Cases 1, 9

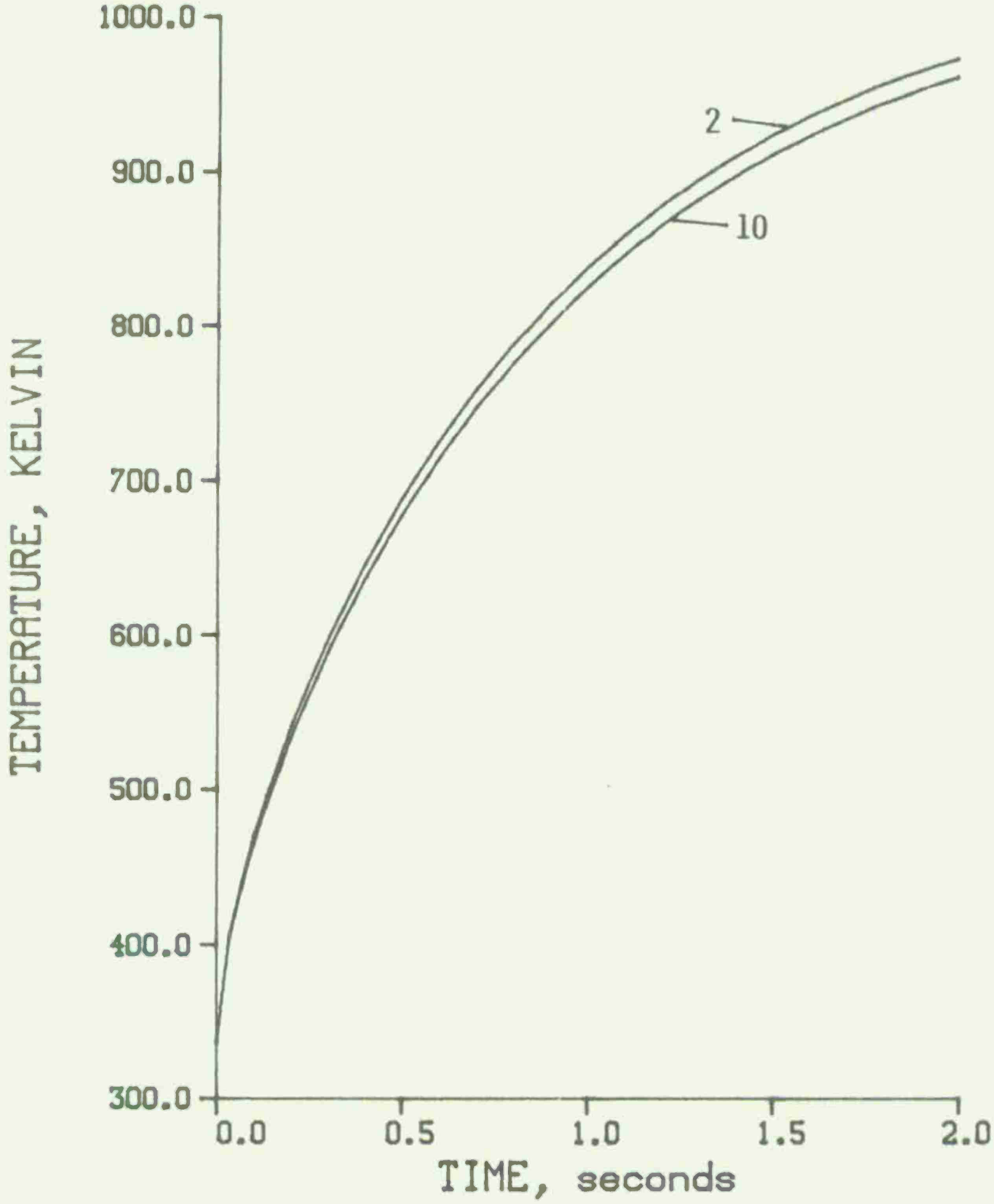


Figure 12. Temperature at the Leading Edge Coating-Metal Interface vs. Time Comparing Effect of Different Densities of Coating, In-Flight Cases 2, 10

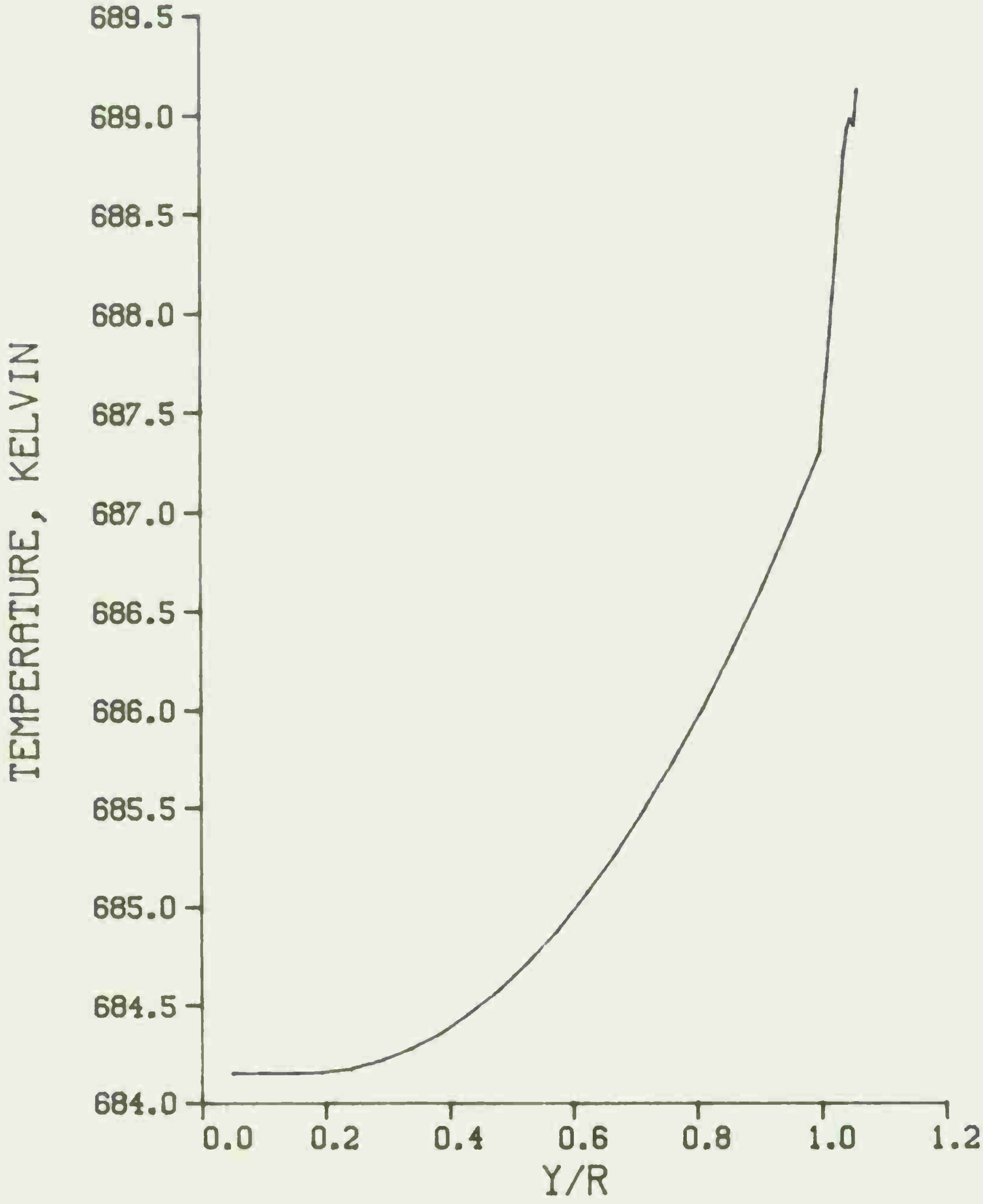


Figure 13. Temperature Profile Across Fin and Coating at P4 for Several Times in the Trajectory, In-Flight Case 1

a. t = 0.5 second

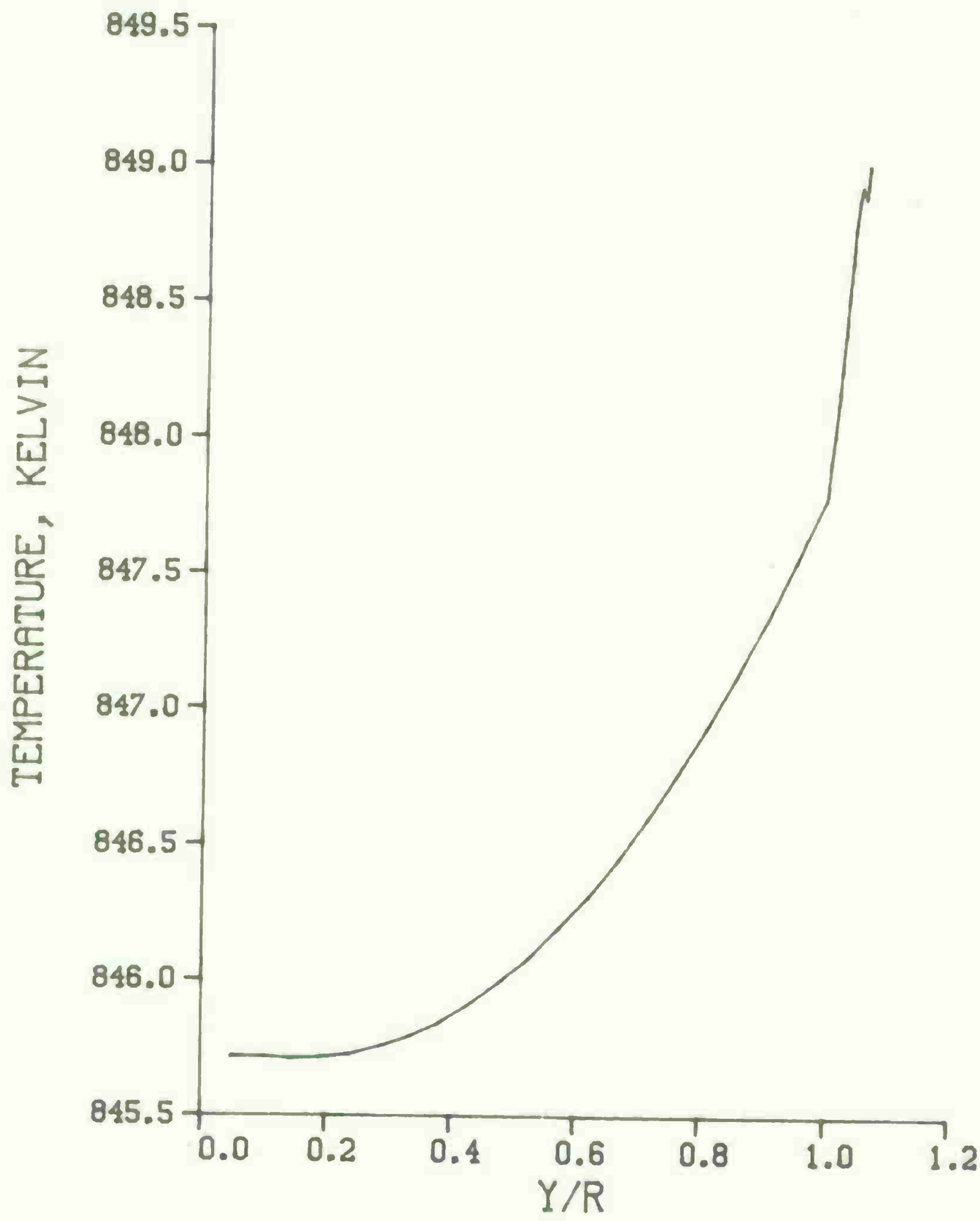


Figure 13. Continued

b. t = 1.0 second

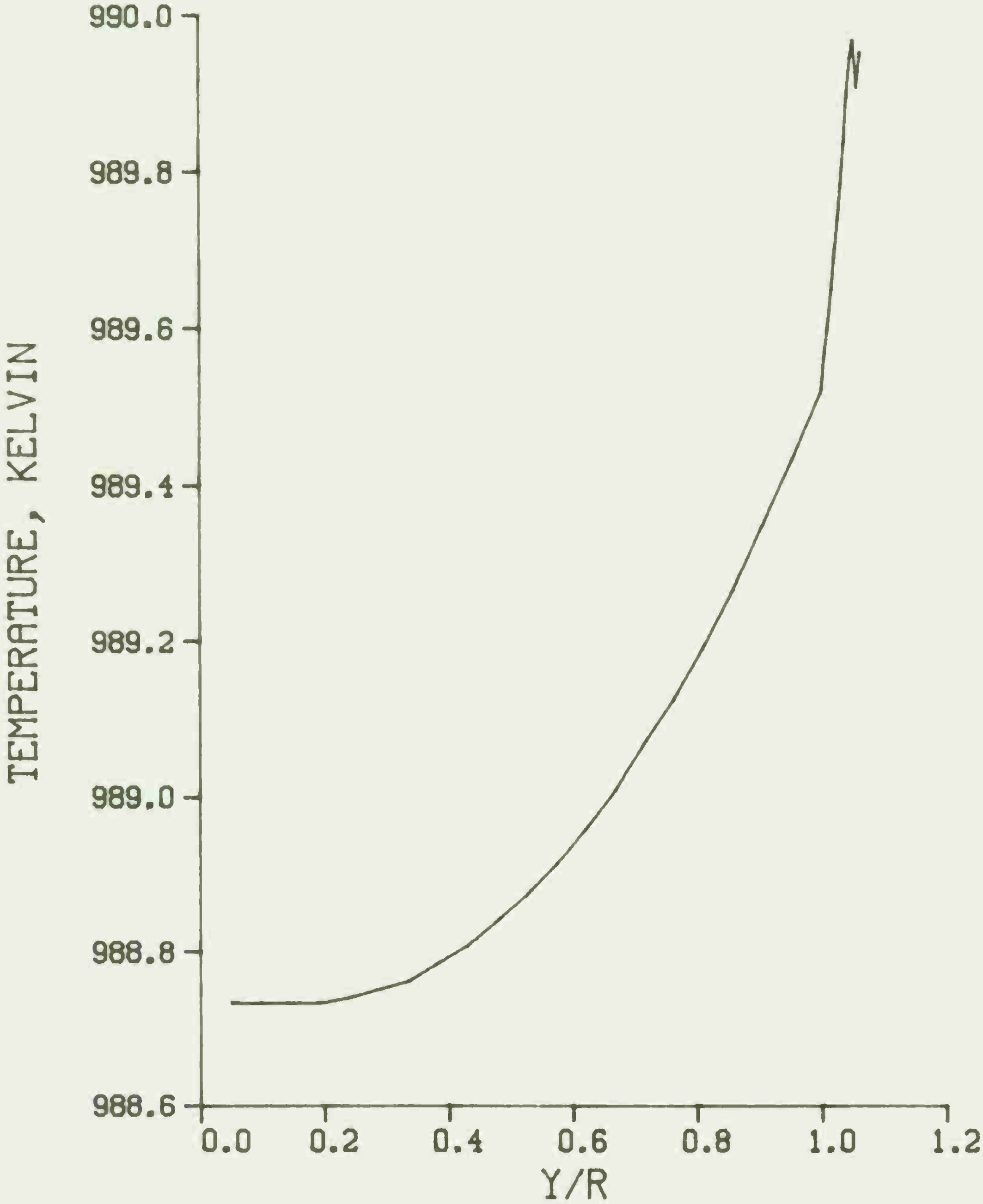


Figure 13. Continued

c. t = 2.0 seconds

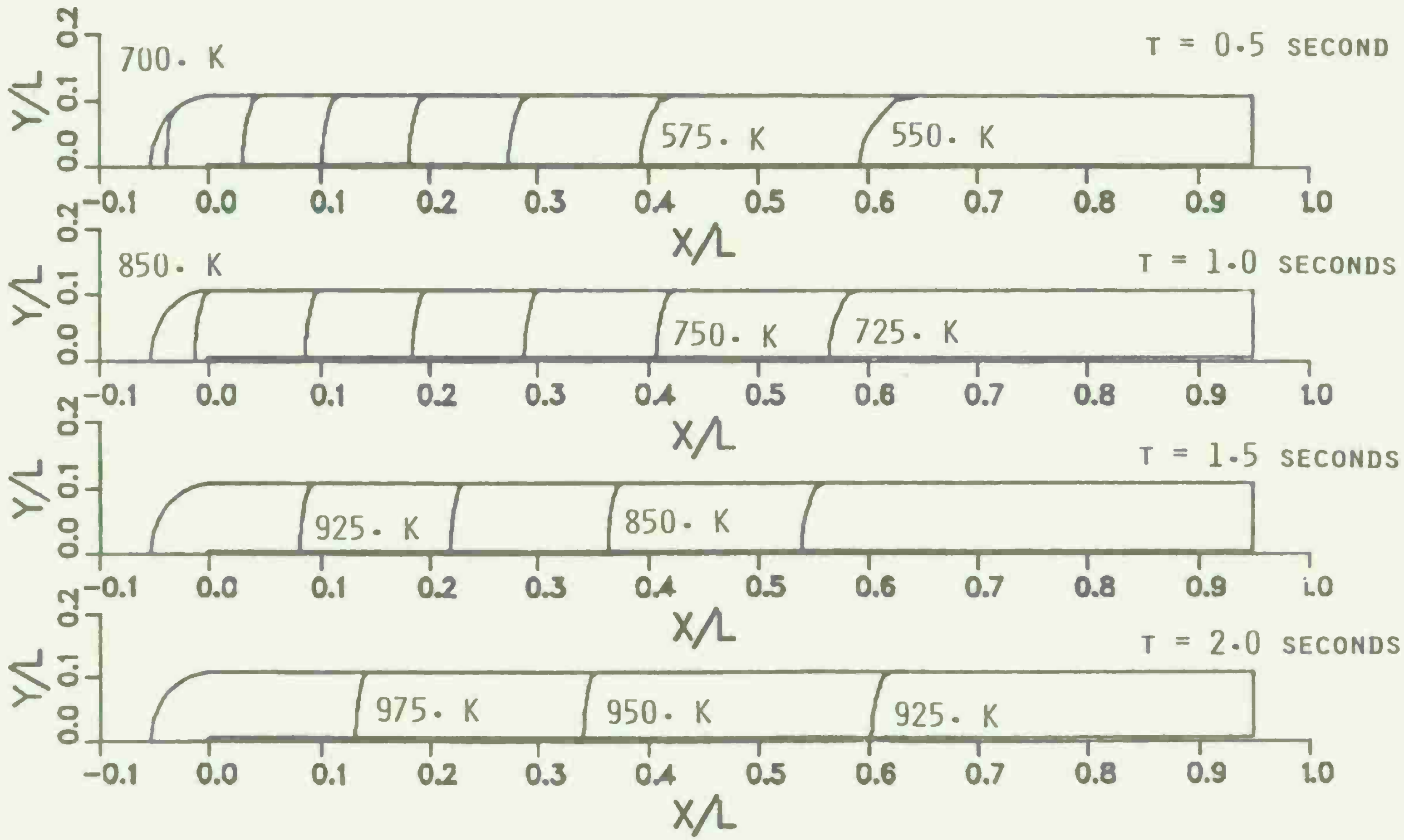


Figure 14. Temperature Contour Plots at Time = 0.5, 1.0, 1.5, 2.0 Seconds, In-Flight Case 1

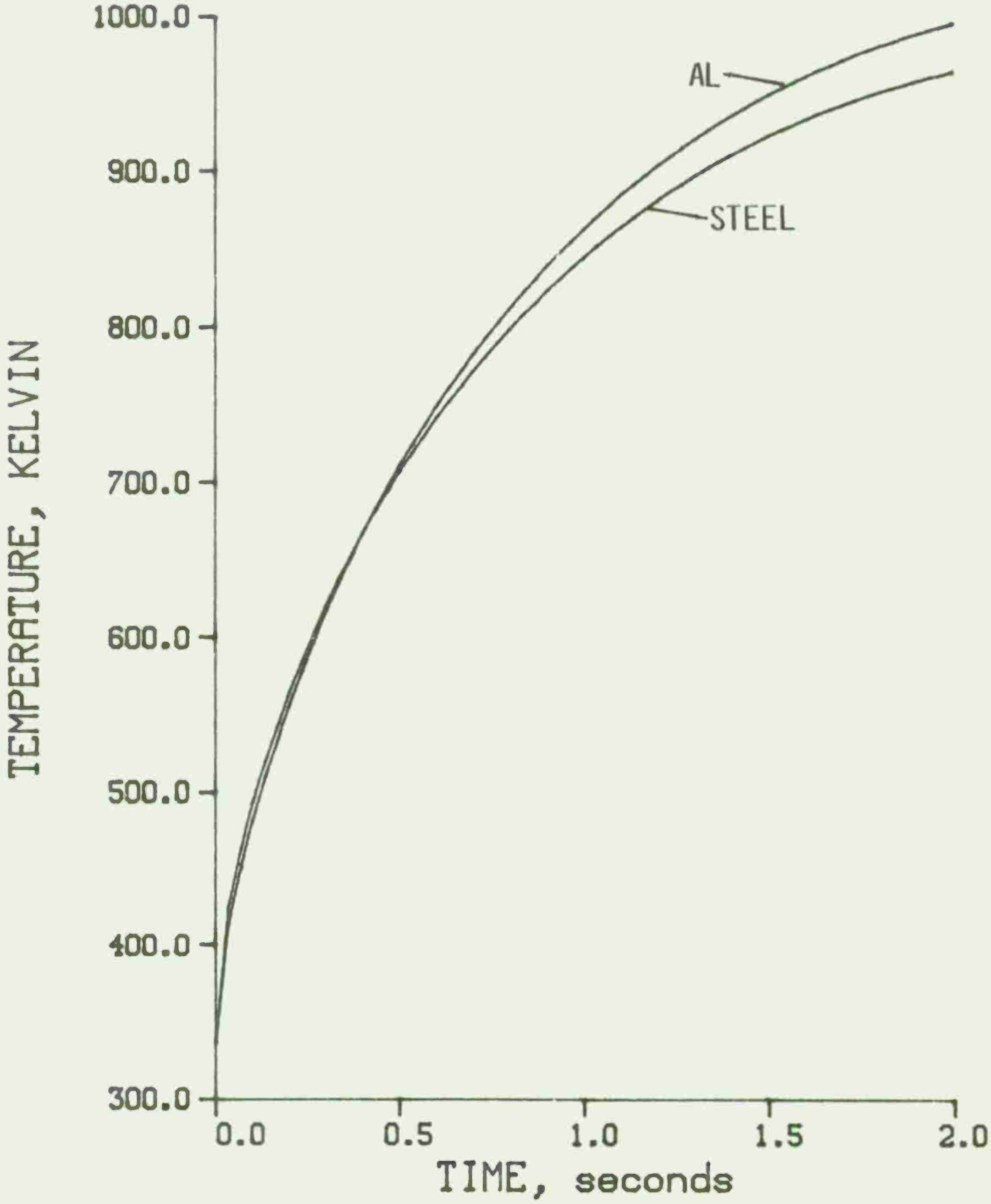


Figure 15. Leading Edge Temperature vs. Time for Coated Aluminum and Uncoated Steel Fins, In-Flight Cases 1, 8

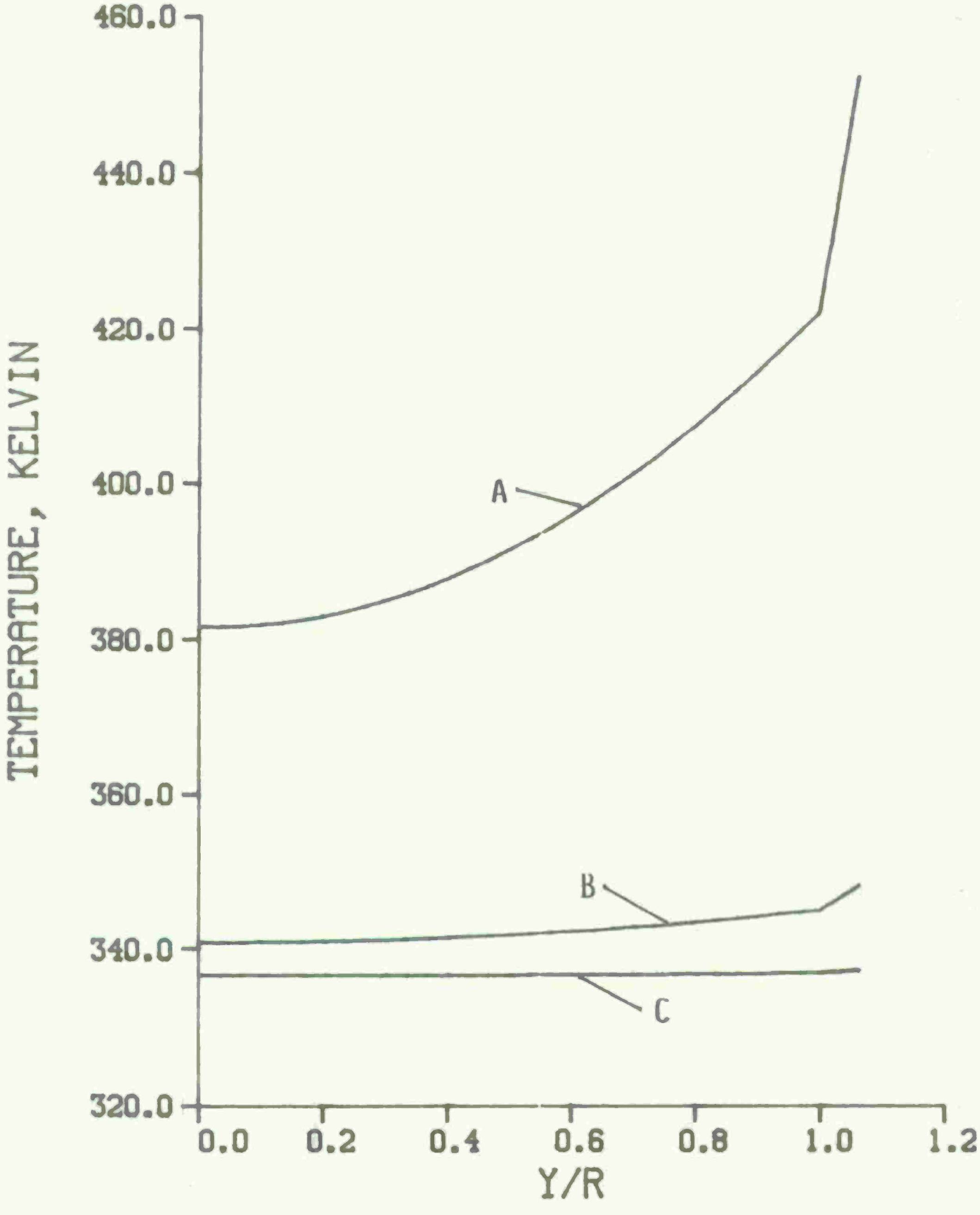


Figure 16. In-Depth Temperature vs. Position for Several Values of the Heat Transfer Coefficient at Time = 0.01 Second, In-Bore Cases A, B, C

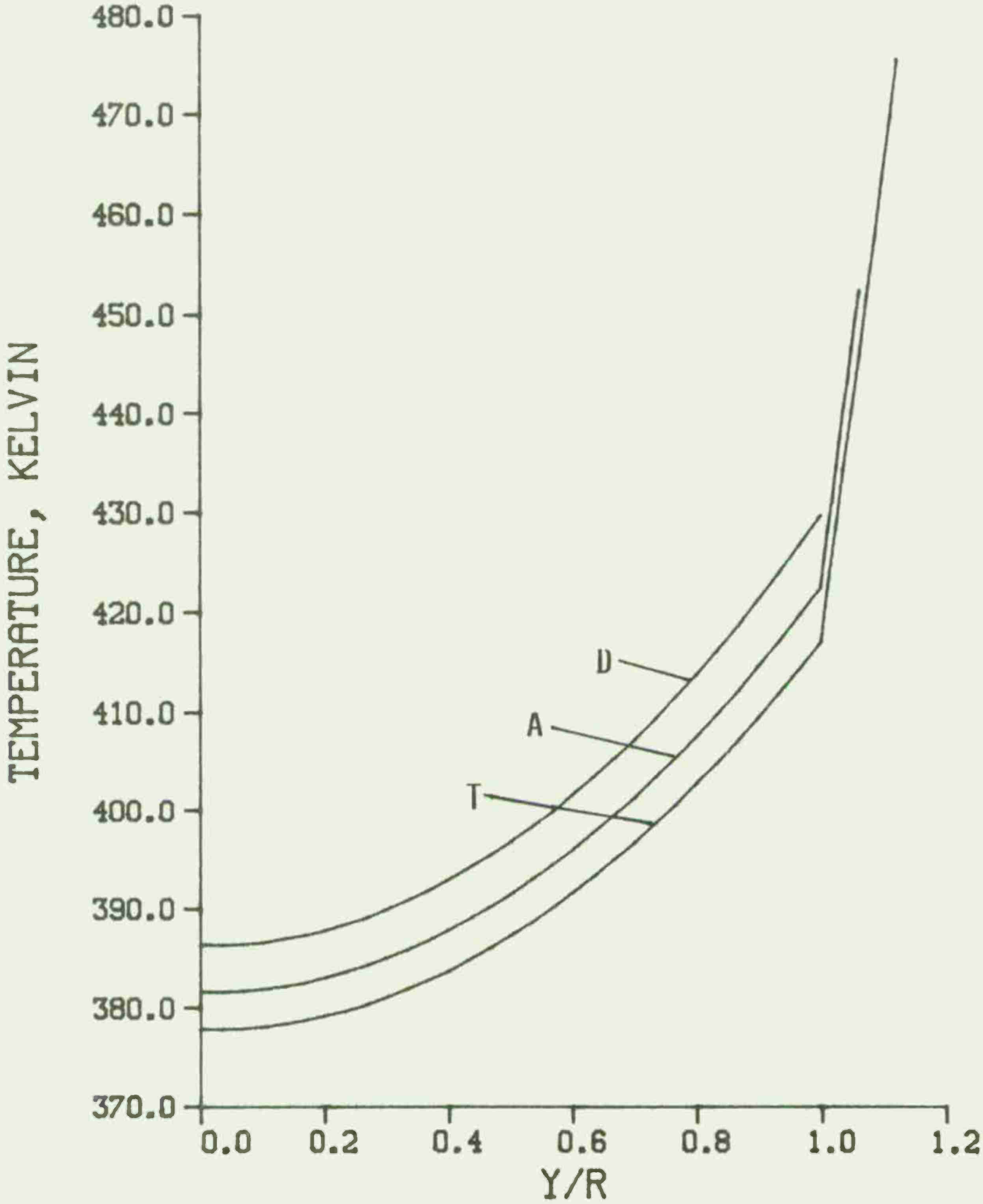


Figure 17. In-Depth Temperature vs. Position Comparing the Effect of the Coating Thickness at Time = 0.01 Second, In-Bore Cases A, D, T

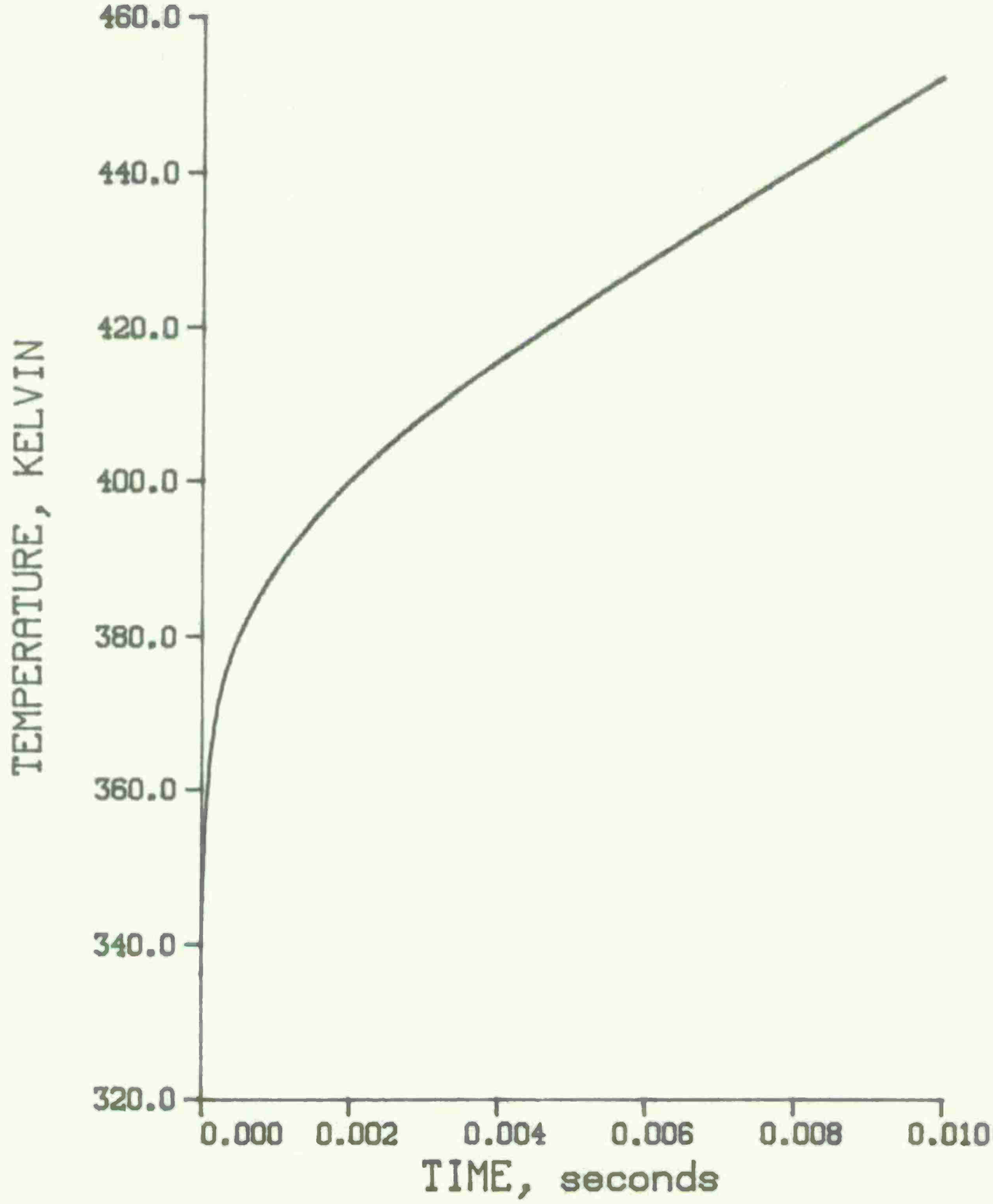


Figure 18. Surface Temperature vs. Time, In-Bore Case A

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1. Suchsland, K.E., "Aerothermal Assessment of Projectiles Using the ABRES Shape Change Code (ASCC)," Acurex Report TM-80-31-AS, June 1980.

2. Dwyer, H.A., Kee, R.J., and Sanders, B.R., "Adaptive Grid Method for Problems in Fluid Mechanics and Heat Transfer," AIAA Journal, Vol. 18, No. 10, October 1980, pp. 1205-1212.

LIST OF SYMBOLS

dR	change in range	[km]
h	heat transfer coefficient (1-D)	[W/m^2 - K]
h	heat transfer coefficient (2-D)	[kg/m^2 - s]
H	enthalpy	[kJ/kg]
k	thermal conductivity	[W/m - K]
l/d	projectile length to diameter ratio	[cm/cm]
L	chord length of section examined	[m]
L_1	length for nondimensionalizing arc length	[m]
R	leading edge radius	[mm]
S	surface arc length from leading edge	[mm]
t	time	[secs]
T	temperature	[K]
T_{aw}	recovery temperature	[K]
T_{wall}	wall temperature	[K]
x	one-dimensional cross fin coordinate	[mm]
x	two-dimensional chordwise coordinate	[mm]
Y	two-dimensional cross fin coordinate	[mm]
η, ξ	generalized coordinates for 2D computations	[mm]

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